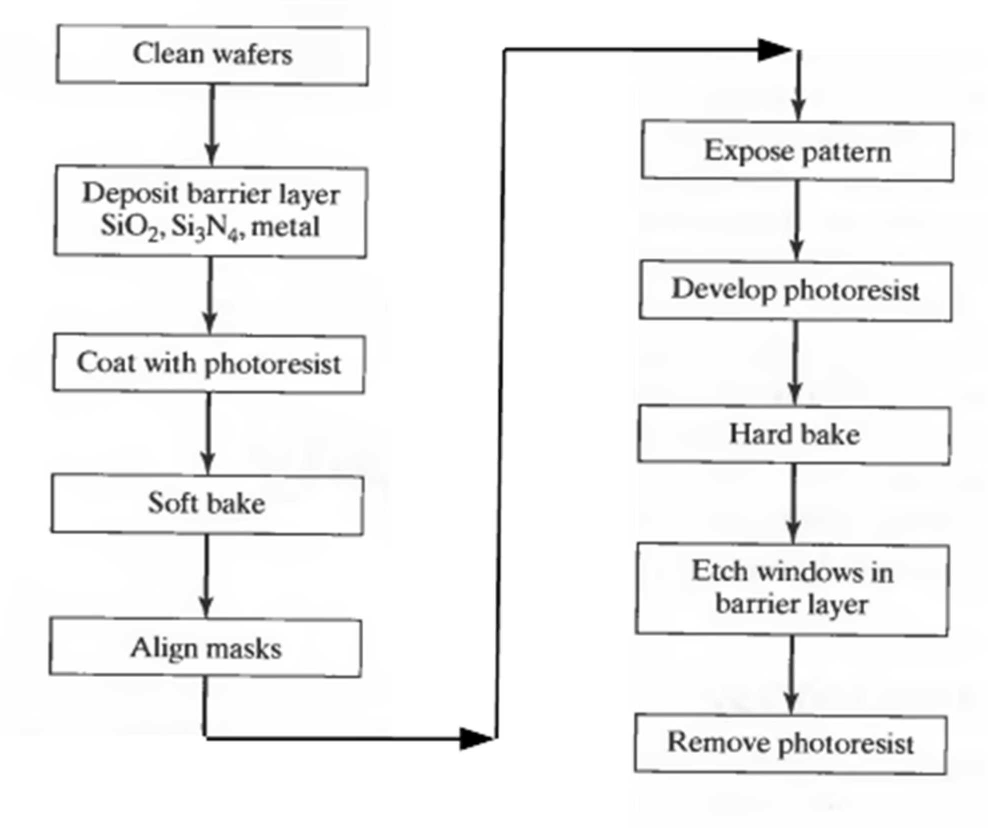
لیتوگرافی

Lithography

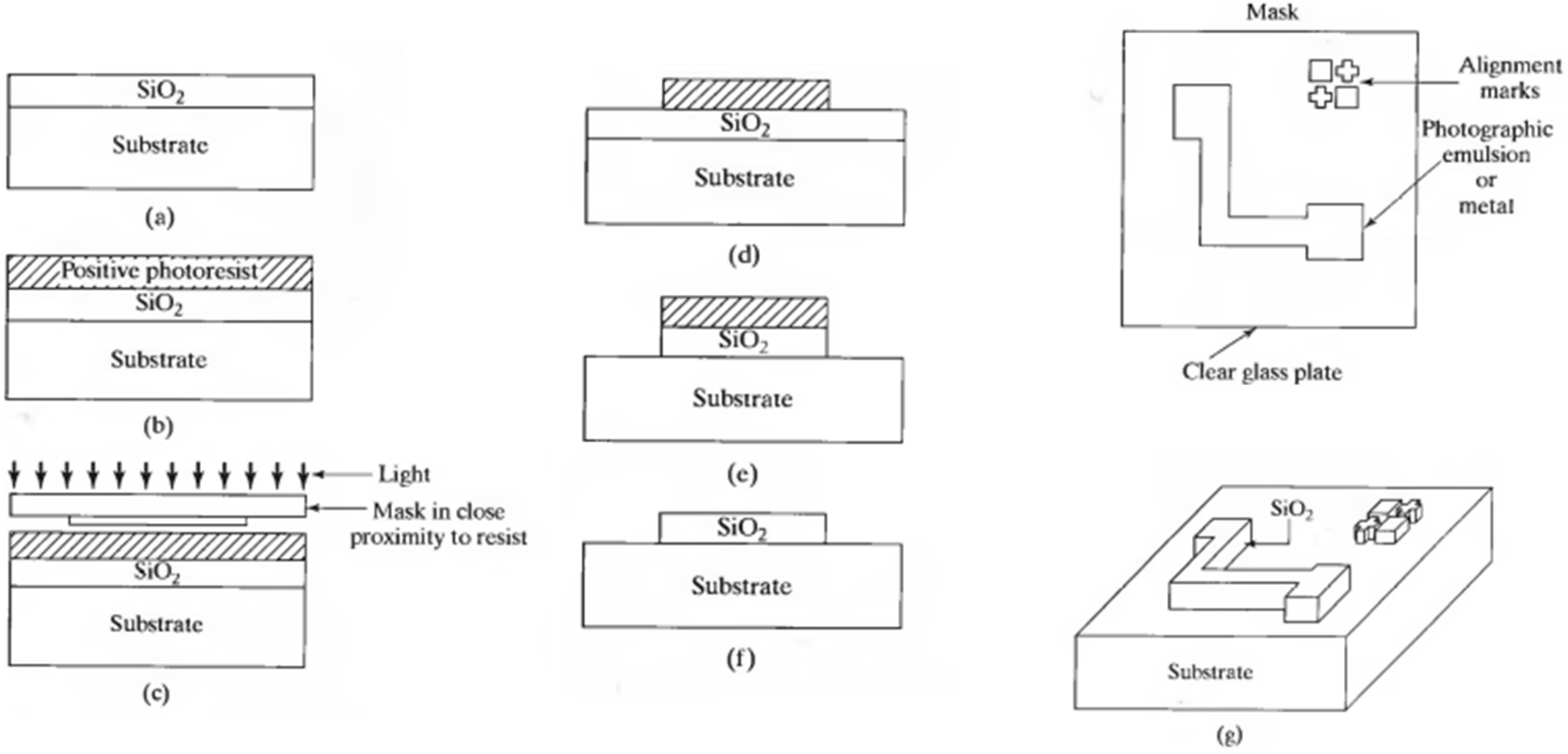
لیتوگرافی- فرایند کلی

In the manufacturing steps, materials have to be removed only in certain places. The process enabling us to define these places is lithography. The complete name is photolithography, but it is also called as lithography or litho in the industry.



لیتوگرافی- فرایند کلی

Drawings to show a wafer at various processing steps.

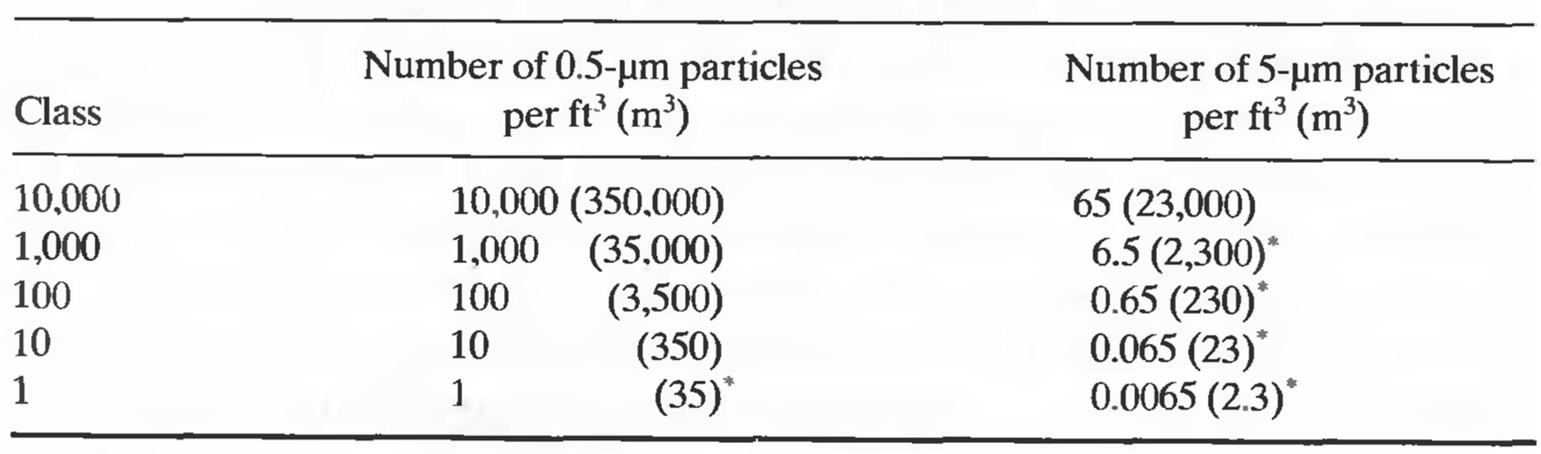


اتاق تمیز

Wafer processing is done at clean rooms.

Normal room air has several million dust particles exceeding a size of 0.5 micron.

Clean rooms are classified by rating numbers:



Class	Number of 0.5-µm particles per ft³ (m³)	Number of 5-µm particles per ft³ (m³)
10,000	10,000 (350,000)	65 (23,000)
1,000	1,000 (35,000)	6.5 (2,300)*
100	100 (3,500)	0.65 (230)*
10	10 (350)	0.065 (23)*
1	1 (35)*	0.0065 (2.3)*

VLSI processing is done in class 1 clean rooms.

اتاق تمیز

مثال: اگر یک ویفر ۲۰۰ میلی متری به مدت یک دقیقه تحت جریان هوایی با سرعت ۳۰ متر بر دقیقه در یک اتاق تمیز کلاس ۱۰ قرار گیرد چند تا گرد و غبار روی آن خواهد نشست؟

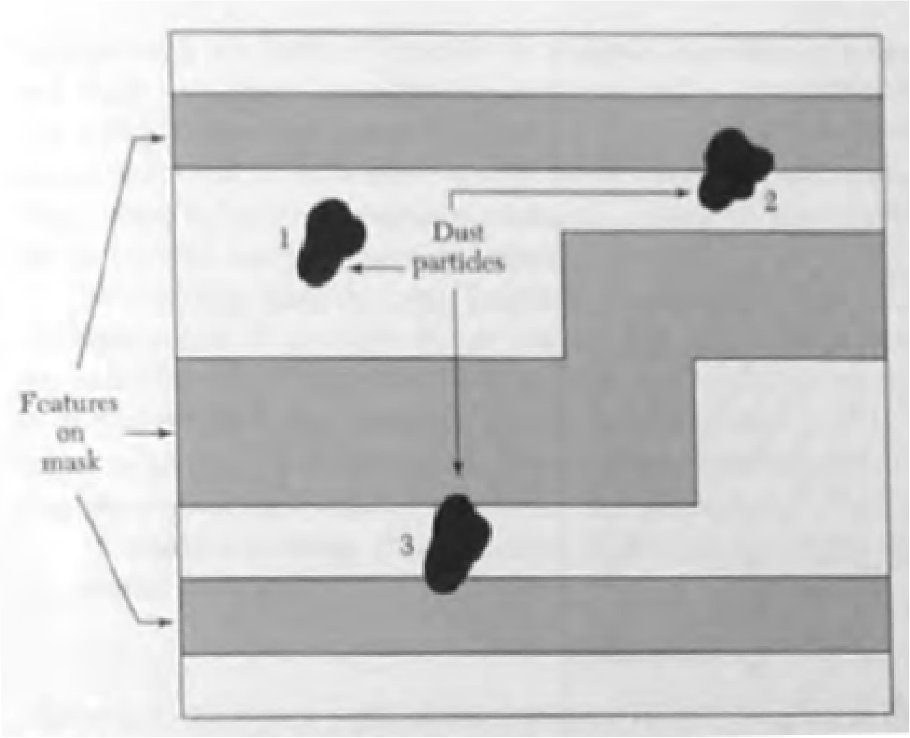
Air volume that goes over the wafer :

$$V = 30\frac{m}{min} \times \pi(\frac{0.2m}{2})^2 \times 1min = 0.942m^3$$

اتاق کلاس ۱۰ شامل ۳۵۰ ذره بزرگتر از نیم میکرون در یک مترمکعب می باشد. بنابراین تعداد ذرات روی ویفر خواهد شد:

$$0.942 \times 350 = 330$$

جاهای مختلفی که ذرات گرد و غبار می توانند روی ماسک بنشینند



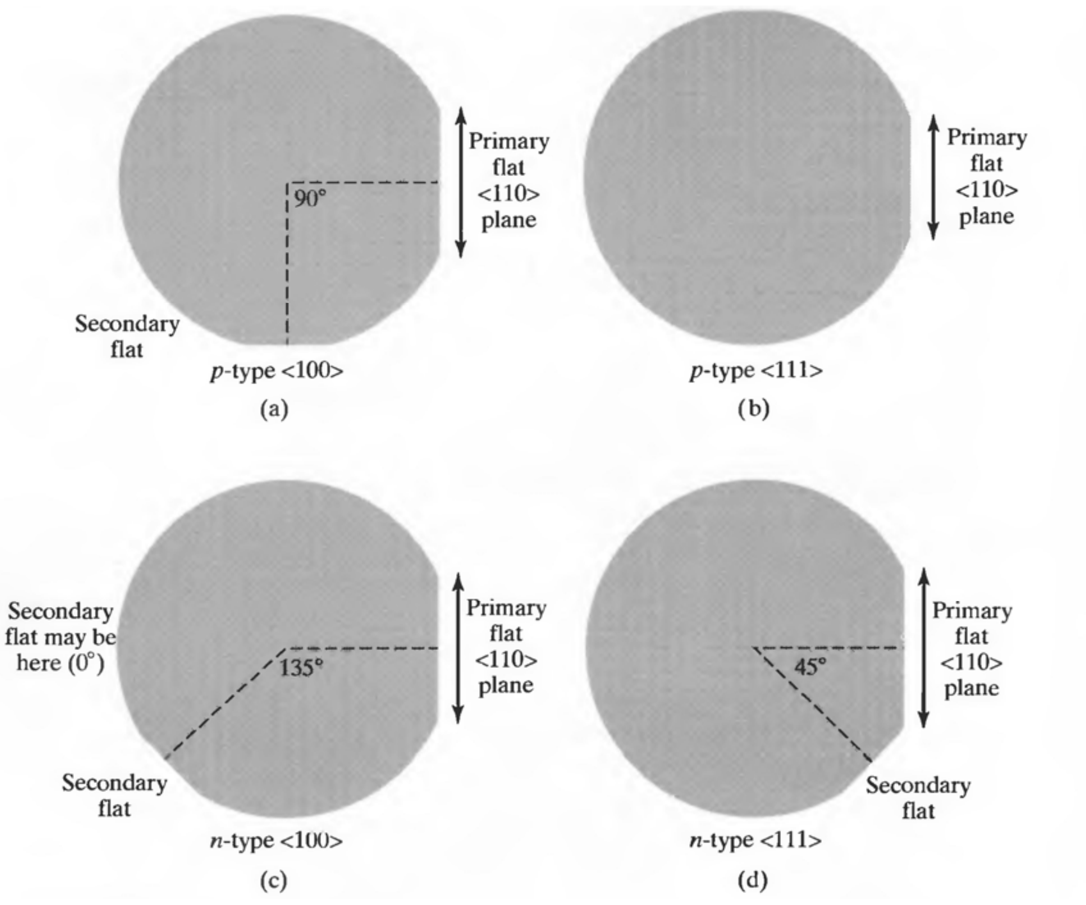
تمیز کردن ویفر

Wafer identification flats.

These flats are ground into the silicon ingot before it is sliced into wafers.

Original silicon wafers have metallic gray color. After formation of SiO2 on the surface of the wafer, depending on the thickness of SiO2 the surface will have a color.

After processing different regions of a wafer will have different thickness and so the IC will be multicolored.



تمیز کردن ویفر

Prior to use wafers are cleaned. The important and general use solution for cleaning is deionized (DI) water. DI water is highly purified and filtered to remove all traces of ionic, particulate, and bacterial contamination.

Theoretical resistivity of pure water at 25 degrees Celsius is 18.3 Mohm-cm. Basic DI water systems achieve resistivities of 18 Mohm-cm with fewer than 1.2 colonies of bacteria per milliliter, and with no particles larger than 0.25 micron.

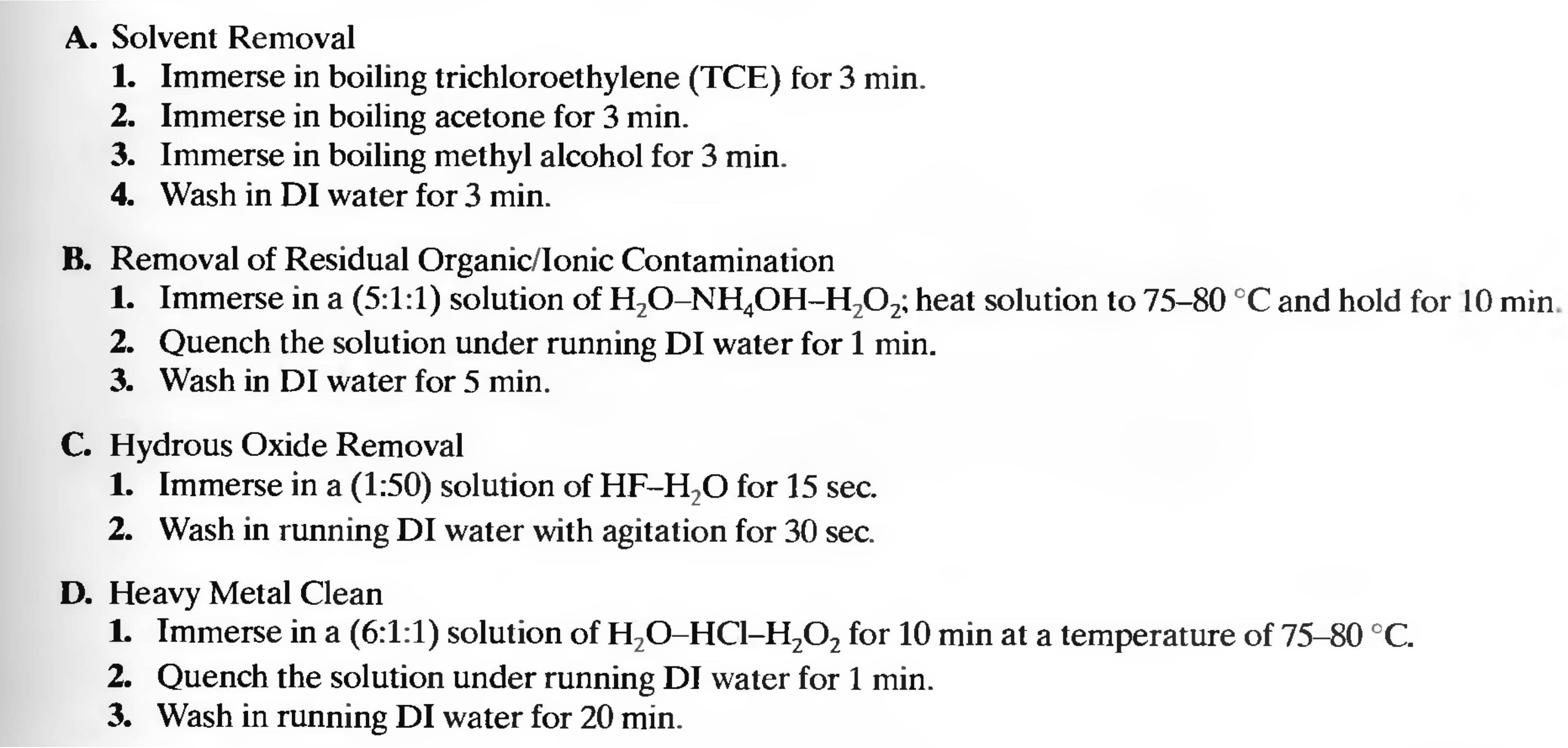
General rules for cleaning any type of wafers are:

1- Ultrasonic cleaning in DI water for 3 min
2- Dry by using dry N2 gas gun
3- Ultrasonic cleaning in acetone for 3 min
4- Ultrasonic cleaning in IPA for 3 min
5- Dry by using dry N2 gas gun

If the wafers are oily then prior to the above steps, they are ultrasonic cleaned in soap solution for 3 min.

تمیز کردن ویفر

A typical cleaning procedure for silicon wafers is as follows:



A. Solvent Removal
  - **1.** Immerse in boiling trichloroethylene (TCE) for 3 min.
  - **2.** Immerse in boiling acetone for 3 min.
  - **3.** Immerse in boiling methyl alcohol for 3 min.
  - **4.** Wash in DI water for 3 min.

B. Removal of Residual Organic/Ionic Contamination
  - **1.** Immerse in a (5:1:1) solution of H_2O–NH_4OH–H_2O_2; heat solution to 75–80 °C and hold for 10 min.
  - **2.** Quench the solution under running DI water for 1 min.
  - **3.** Wash in DI water for 5 min.

C. Hydrous Oxide Removal
  - **1.** Immerse in a (1:50) solution of HF–H_2O for 15 sec.
  - **2.** Wash in running DI water with agitation for 30 sec.

D. Heavy Metal Clean
  - **1.** Immerse in a (6:1:1) solution of H_2O–HCl–H_2O_2 for 10 min at a temperature of 75–80 °C.
  - **2.** Quench the solution under running DI water for 1 min.
  - **3.** Wash in running DI water for 20 min.

لایه پوششی (سدی)

After cleaning, the silicon wafer is covered with a material that serves as a barrier.

The most common barrier material is SiO_2. Silicon nitride (Si_3N_4), polysilicon, photoresist, and metals are also used.

Barrier materials are coated on the wafer surface by using deposition techniques, such as: thermal oxidation, chemical vapour deposition, sputtering, vacuum evaporation, and spin coating.

لایه حساس به نور (فوتورزیست)

After barrier layer, the wafer will be coated with a light sensitive chemical called photo resist, sometimes called “resist”.

To ensure good photoresist adhesion, the surface must be clean and dry. For some surfaces in order to promote adhesion, prior to applying photoresist, a adhesion promoter layer such as HMDS is coated on the surface.

After the resist is poured, the wafer will be made to spin at high speed. The solution will spread very thin on the wafer. Depending on the spinning speed and photoresist viscosity a thin photoresist layer will be formed on the surface.

A drying step called soft baking or prebaking is used to improve adhesion and to remove solvent from the resist layer. The soft baking process is specified on the resist data sheet.

Soft baking time: A few minutes   Baking temperature: 80 – 150 °C

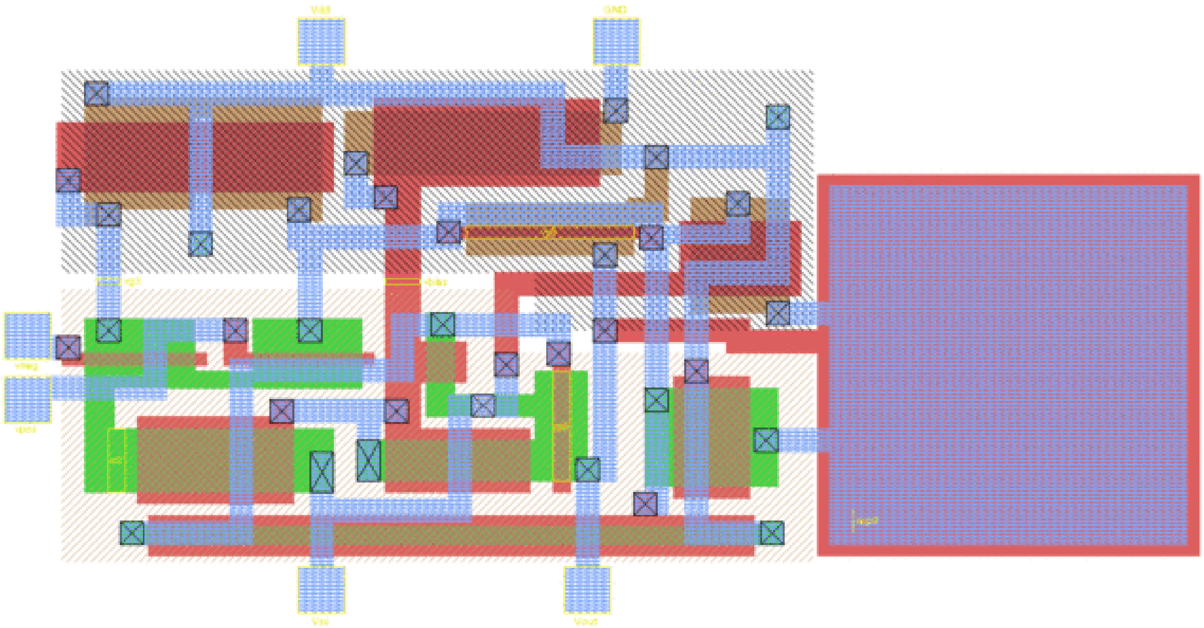
لایه حساس به نور (فوتورزیست)

All these operations would be conducted in a yellow or dark room.

A yellow room and a resist spinning spinner.

ماسک (نقاب)

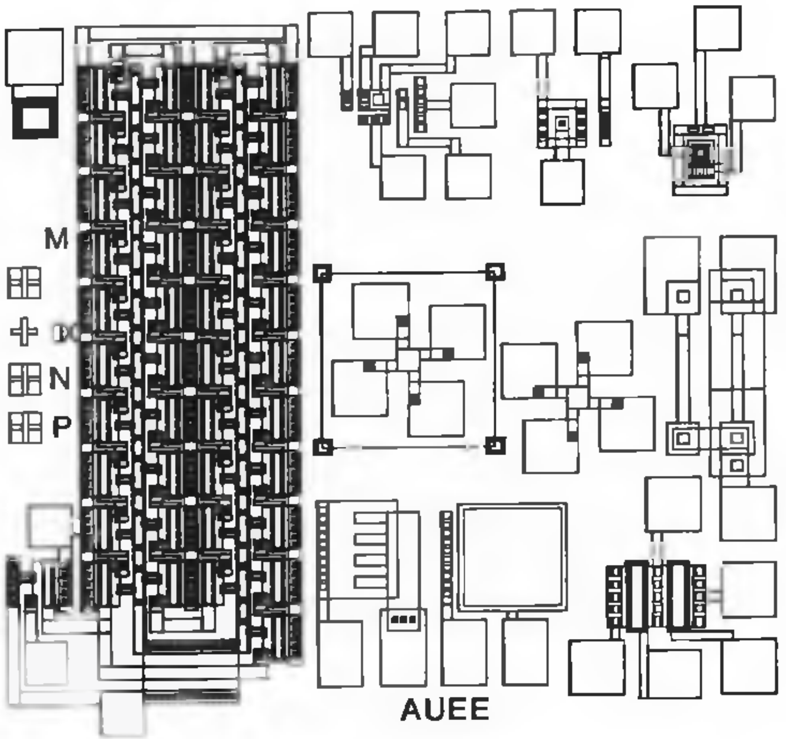
بعد از طراحی مدار الکترونیکی نقشه جانمایی (Layout) مدار طراحی می شود. در ICها چون یک قسمت مرتب تکر می شود بنابراین نقشه جانمایی آنطوریکه در دید اول بنظر می رسد خیلی پیچیده نیست.

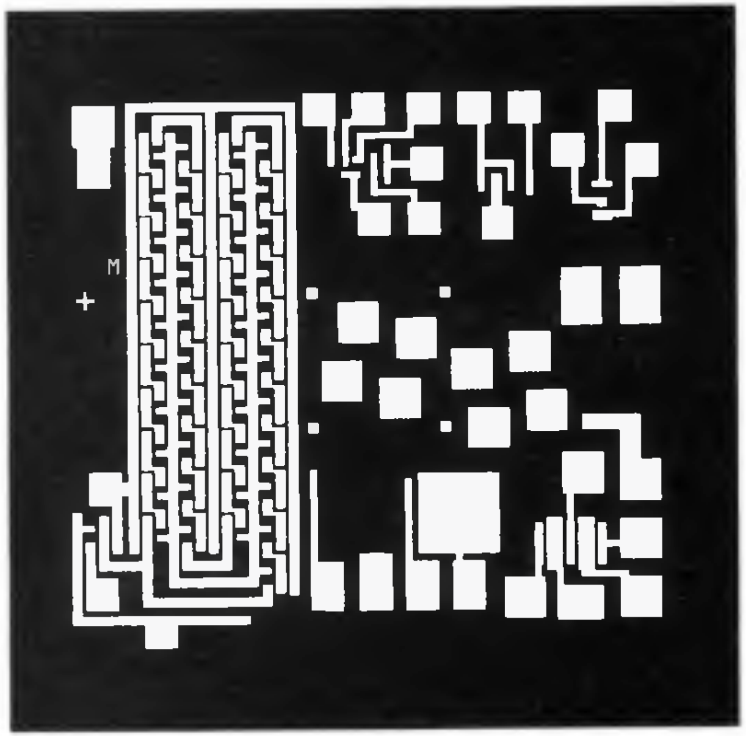


Layout view of a simple CMOS operational amplifier

ماسک (نقاب)

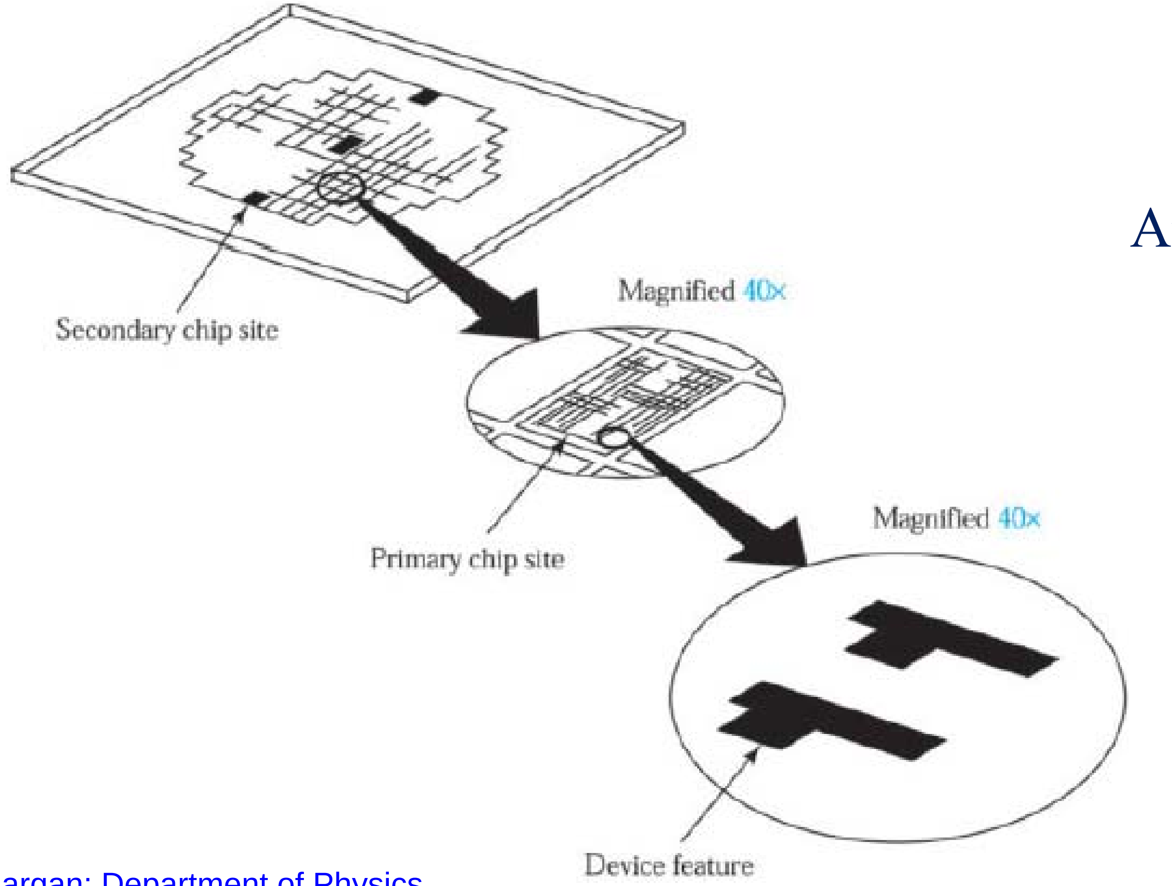
از روی نقشه جانمایی طرح ساخت ماسک ها طراحی می شوند. این طرح ها به صورت یک فایل می باشند. پسوند معروف برای اینگونه از فایلها GDS است.





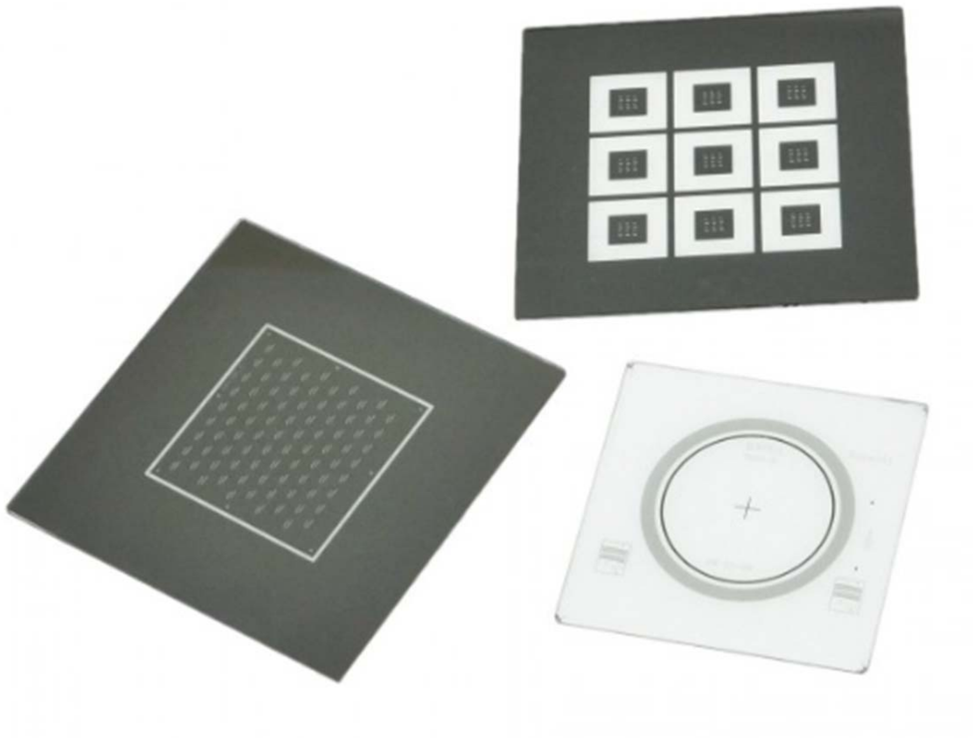
ماسک (نقاب)

طرح ماسک ها که در یک فایل ذخیره شده است توسط یک سیستم کامپیوتری که بسته به نیاز می تواند سیستم پرتو الکترونی یا نوری کنترل شونده با کامپیوتر باشد به روی زیرلایه هایی که شیشه سودالایم یا کوارتز هستند انتقال داده می شوند. روی این زیرلایه ها از کروم و روی آن ها هم توسط رزیست حساس به نور یا پرتو الکترونی پوشیده شده است.

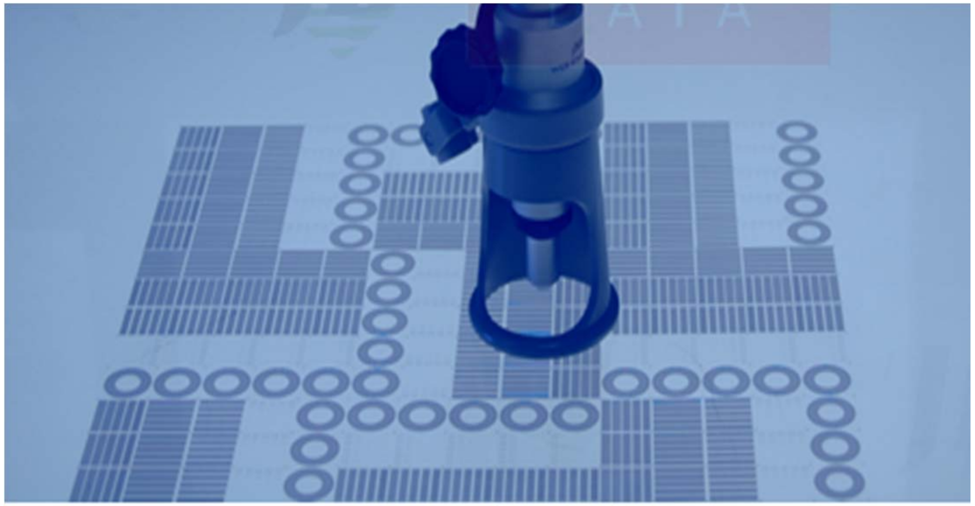


An IC photomask

ماسک (نقاب)



Emulsion Glass Photomask



Emulsion Film Photomask

ماسک (نقاب)

چگالی نقص ها روی یک ماسک مشکل مهمی است که بایستی مورد توجه قرار گیرد. نقص ها روی ماسک ممکن است در حین ساخت ماسک و یا در طی انجام فرایندهای لیتوگرافی ایجاد شوند.

در طی فرایند ساخت IC ممکن است نیاز به ۱۵-۲۰ ماسک باشد بنابراین در این شرایط حتی چگالی کم نقص ها هم می تواند مهم باشد چراکه بازده ساخت را پایین می آورد (بازده نسبت تعداد تراشه های خوب به کل تعداد تراشه ها در روی یک ویفر تعریف می شود).

$$Y = exp(-ND_0 A_c)$$

For a processing with $N=10$ mask levels, and defect density of $D_0=0.25$ defect/cm^2 on each mask, yield is 10% for a chip size of 9 cm^2.

تطبیق ماسک با ویفر

After this, the wafer and mask are brought into alignment. The lens system will be adjusted so that the focus is correct. Then light of particular wavelength will be made to fall on the wafer, through the mask, for a short time. Wherever the light has fallen, the chemical reaction would have taken place.

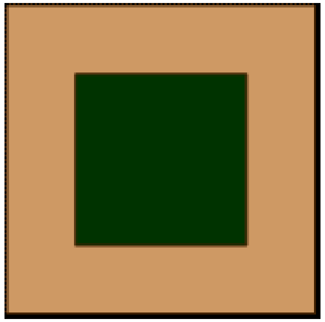
After exposure, it is sent for developing. The wafers are dipped in suitable solutions. Wherever the light has fallen, a chemical reaction would have occurred. Exposed (or not exposed) areas will be dissolved in the developing solution depending on the resist type positive (or negative).

(Alignment Marks) علائم تطبیق

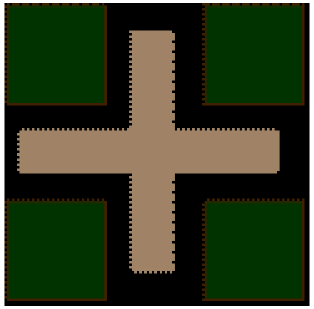
Alignment:

For most of the layers in lithography, alignment to another layer is necessary. For example, in order to make a metal line correctly, it has to be aligned to the previous layer

In ideal situation, everything will align perfectly. However, in practice the alignment will not be perfect and there will be some misalignment. If the line widths and spaces are of the size of say 65 nm, then the alignment tolerance is probably in the range of 10 nm. i.e. We would like it to align perfectly with the previous layer, but a 10 nm misalignment is tolerable.



Box in Box alignment mark



Cross alignment mark

ماده حساس به نور (فوتورزیست)

Positive and negative resists:

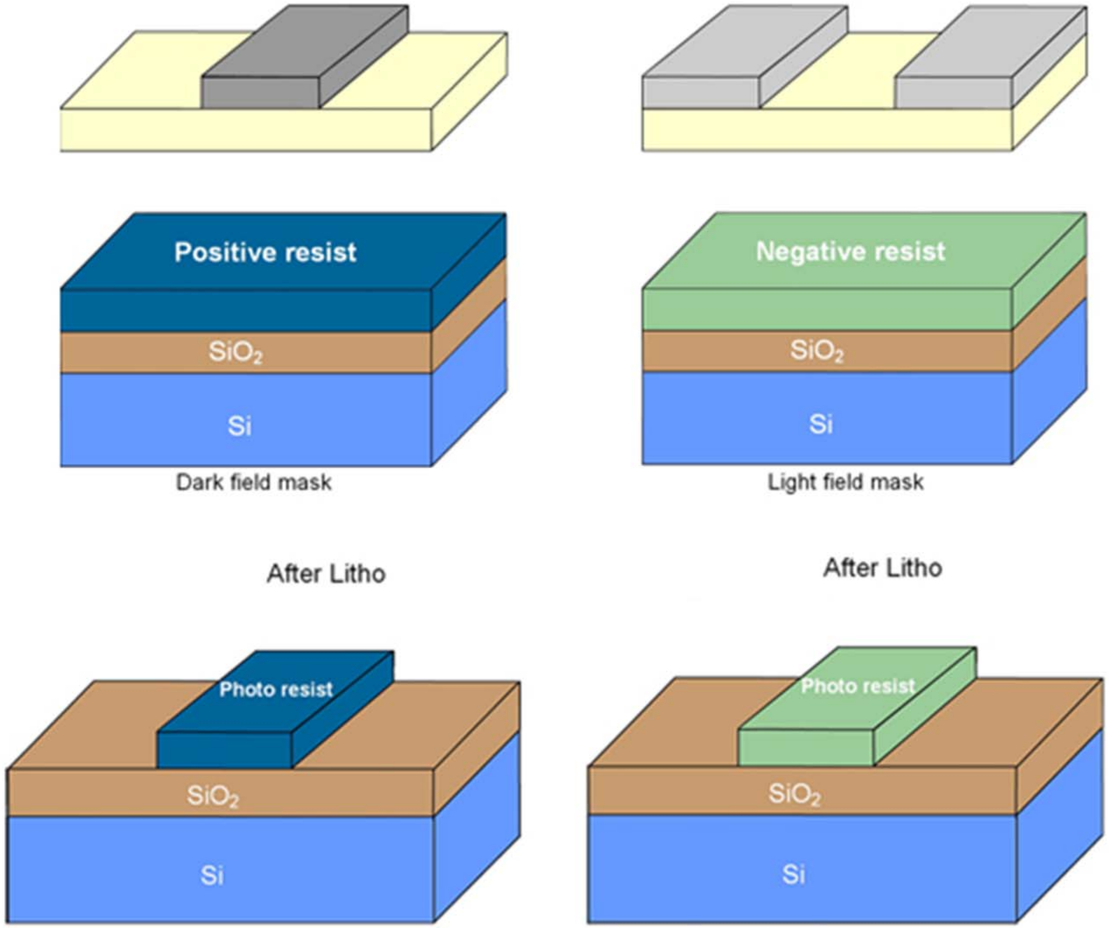
The commonly used resists fall under the category of positive resists. Here, the regions exposed to light dissolve in the next stage of litho process. Thus, the pattern formed on wafer is the same as the pattern present on the mask.

In negative resist the regions exposed to the light will not dissolve but the regions where the light is blocked by the mask will dissolve.

Typical negative photoresists are polymers with photo sensitive chemicals. In presence of light, the polymers will cross link and will be less soluble. In case of positive resists, a photo active compound which is normally not soluble in the developer is used. In presence of light, the compound changes its structure and becomes soluble.

One of the advantages of the positive resist over negative resist is that the process is relatively less sensitive to dust particles.

لایه حساس به نور (فوتورزیست)

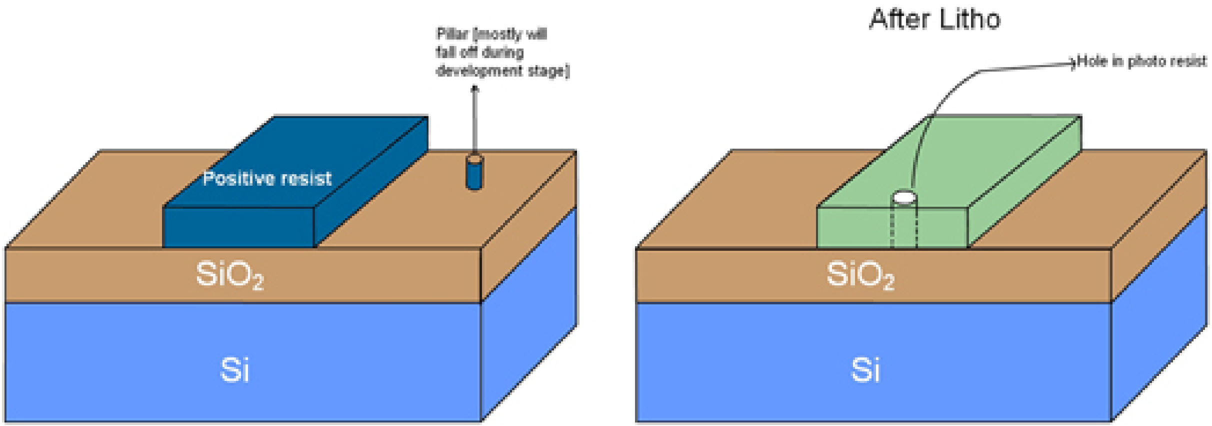


Litho for positive and negative resists.

لایه حساس به نور (فوتورزیست)

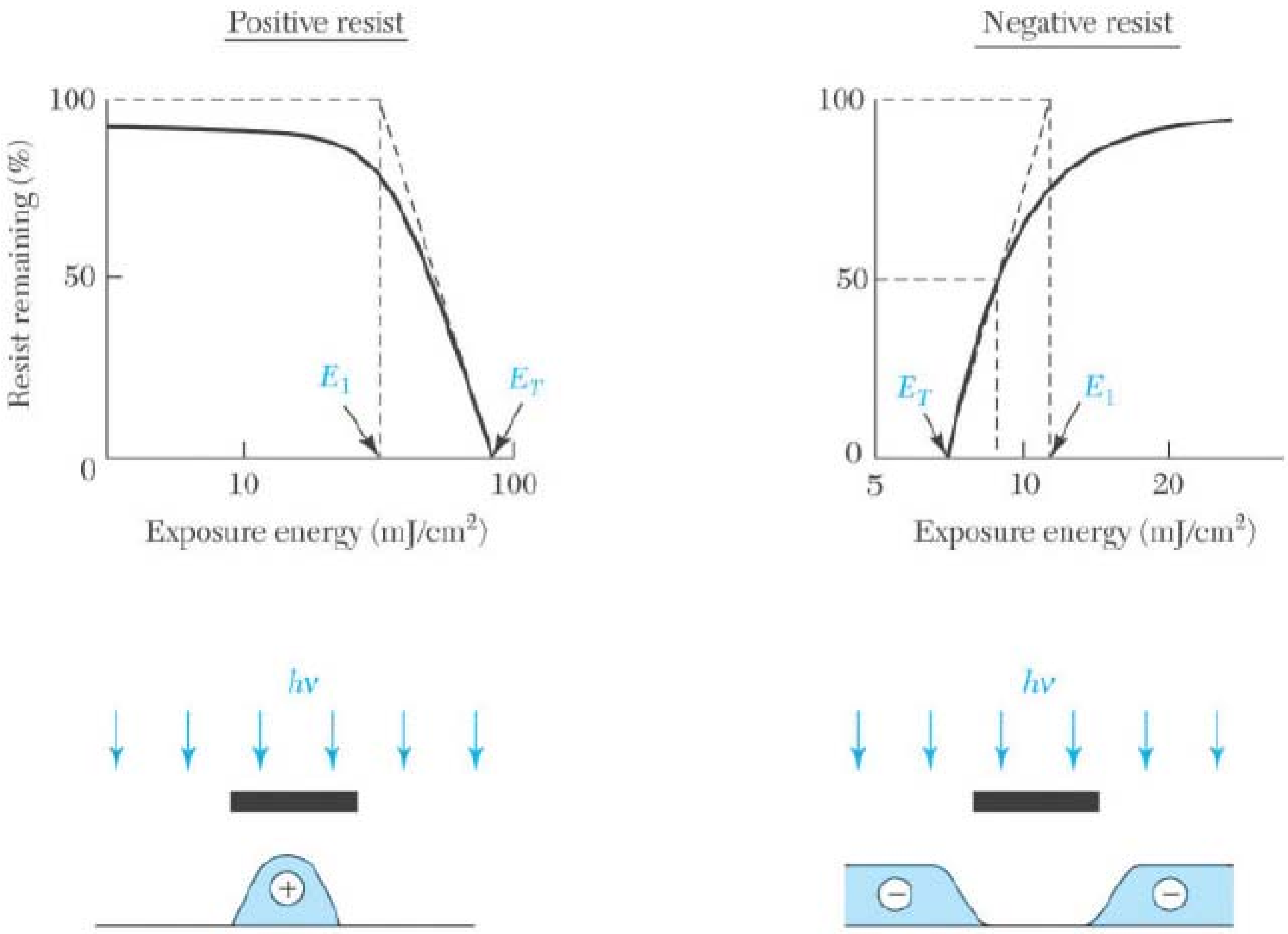
In ideal case, there will not be any dust present and the lithography (exposure and developing) followed by etching will give the required structure.

If the particle is small, then it will block the light in a small area. In positive resist case, the structure, after developing will have small pillar like structures and usually these pillars will not be stable and hence will fall away during the developing process. But if the particle is large, then they will protect the material below them, during the etch process.



In case of negative resist, even if the particle is small, it will result in a pinhole during developing stage. Thus the structure will not be formed correctly for small as well as large dust particle. Hence, positive resist process is relatively more robust.

لایه حساس به نور (فوتورزیست)



Exposure response curve and resist image after development

لایه حساس به نور (فوتورزیست)

حساسیت یک رزیست مثبت به صورت حداقل انرژیی که باعث حل کامل فوتورزیست می شود تعریف می شود. این حداقل انرژی در شکل قبلی با E_T نشان داده شده است.

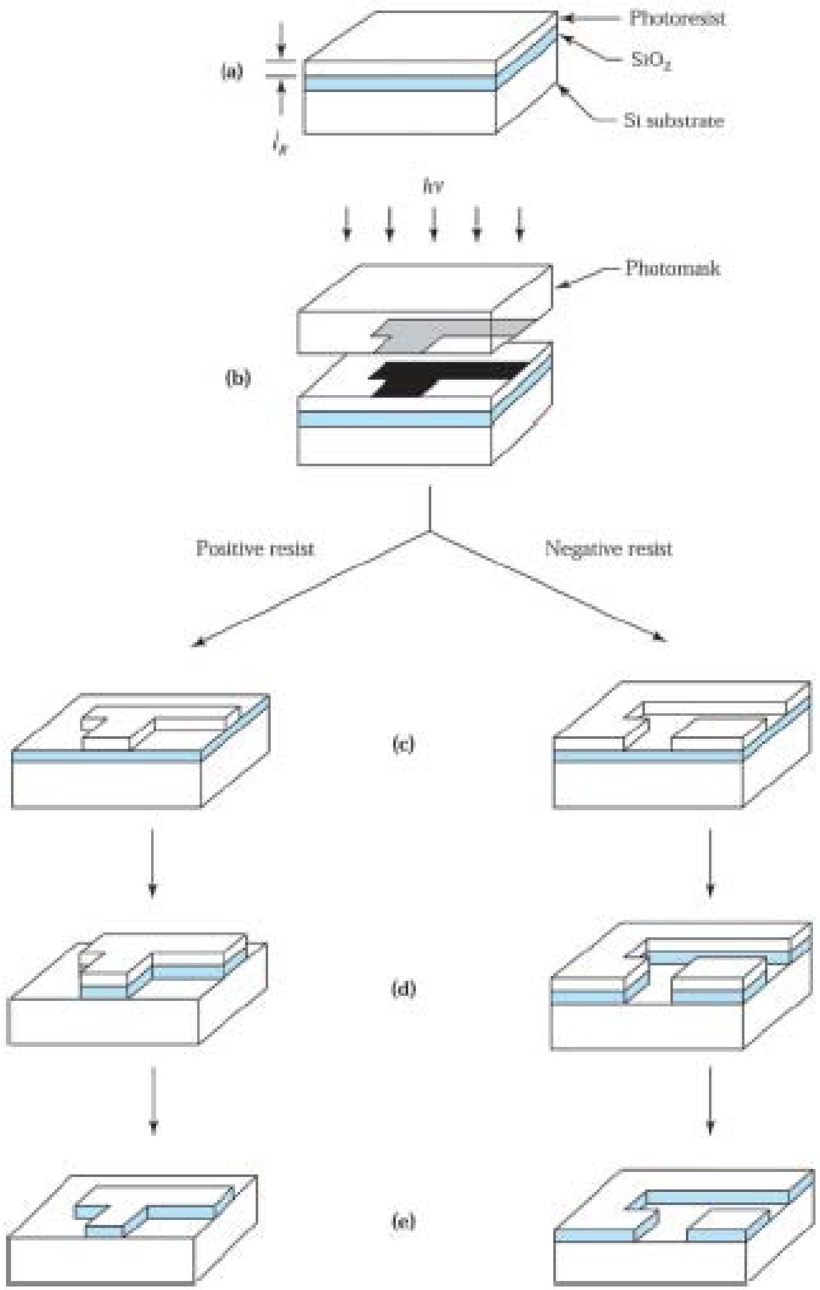
علاوه بر حساسیت برای یک رزیست کنتراست هم تعریف می شود که با رابطه زیر داده می شود:

$$\gamma \equiv \left[\ln\left(\frac{E_T}{E_1}\right)\right]^{-1},$$

هر چه کنتراست بالاتر باشد الگوی رزیست انتقال یافته بر روی ویفر تیزتر خواهد بود.

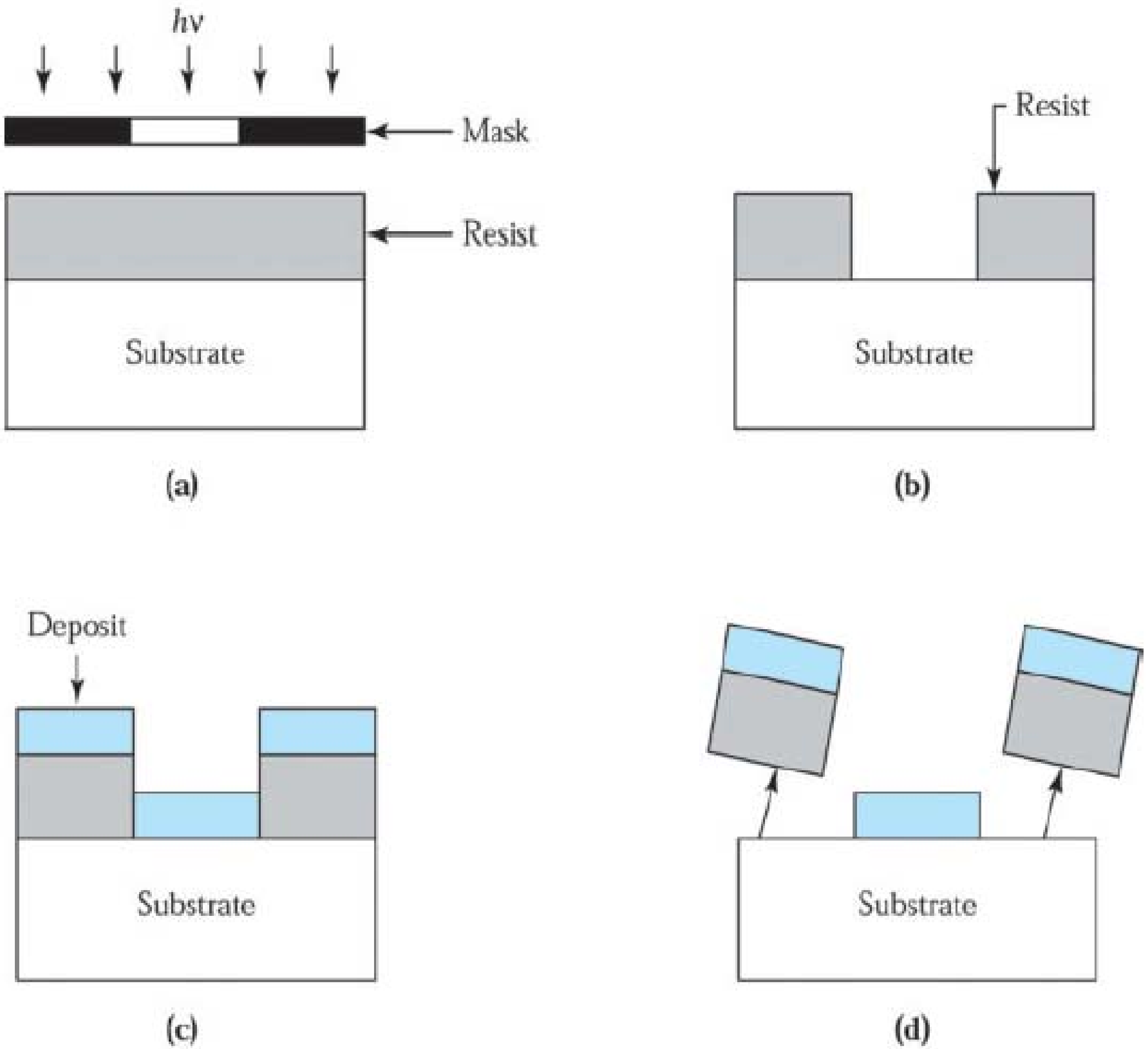
در مورد فوتورزیست منفی حساسیت مقدار انرژیی تعریف می شود که باعث می شود نصف ضخامت رزیست بعد از دولوپ بماند

لایه حساس به نور (فوتورزیست)



Comparing pattern transfer on a wafer with using positive and negative resists.

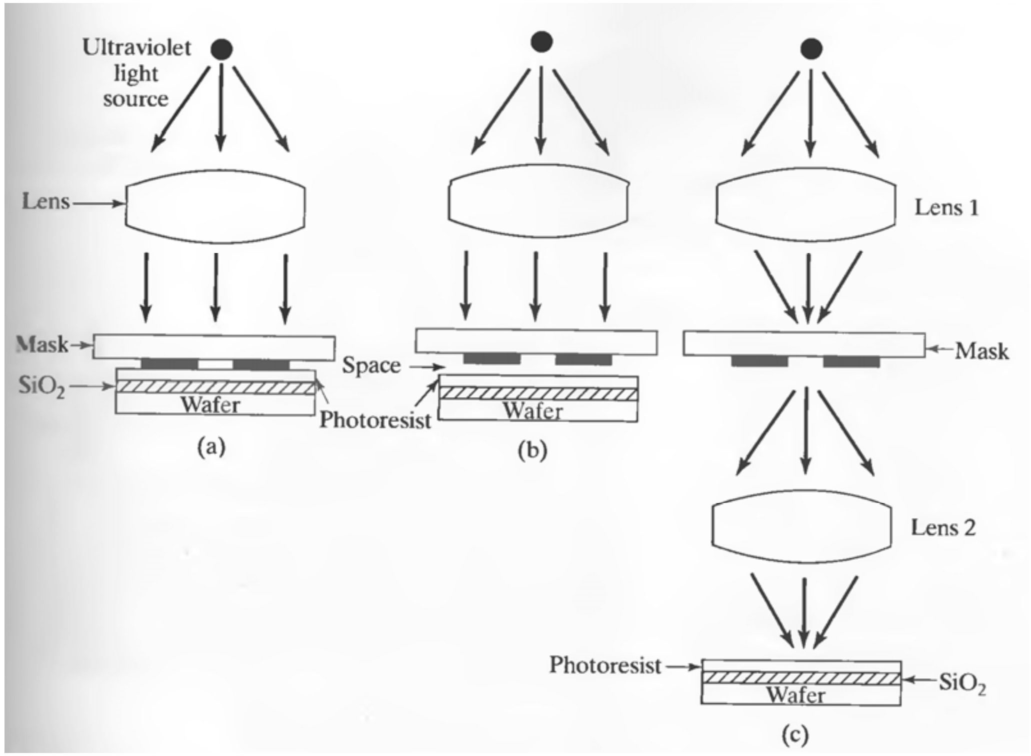
فرایند لیفت-آف



Liftoff process for pattern transfer.

روش های چاپ

Schematic view of printing techniques: (a) contact printing, (b) proximity printing, and (c) projection printing.

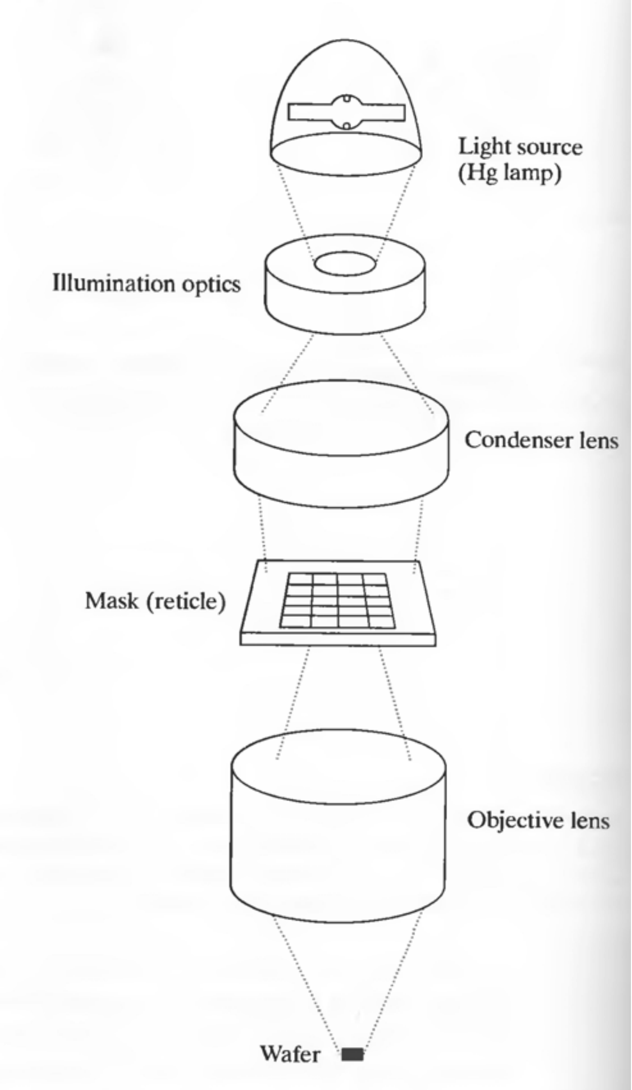


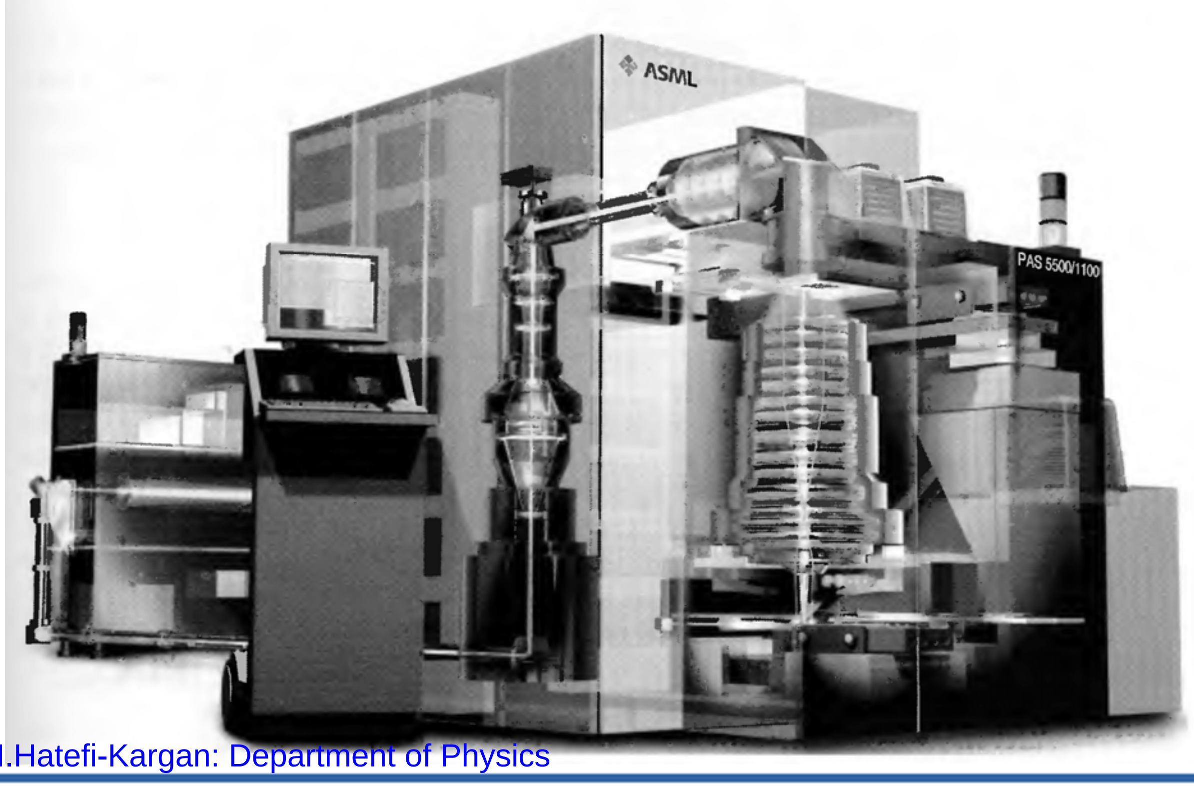
در چاپ نزدیک فاصله بین ماسک و ویفر حدود ۱۰ الی ۵۰ میکرومتر است و کوچکترین چیزی که می توان ساخت تقریباً با رابطه زیر داده می شود:

$$CD = \sqrt{\lambda g}$$

روش های چاپ

For large diameter wafers it is impossible to achieve uniform exposure and to maintain alignment between mask levels, particularly for submicron feature sizes. In this case a direct step-on-wafer projection system is used. A single die image is projected on the wafer surface. The wafer is moved from die site to die site.





قدرت تفکیک

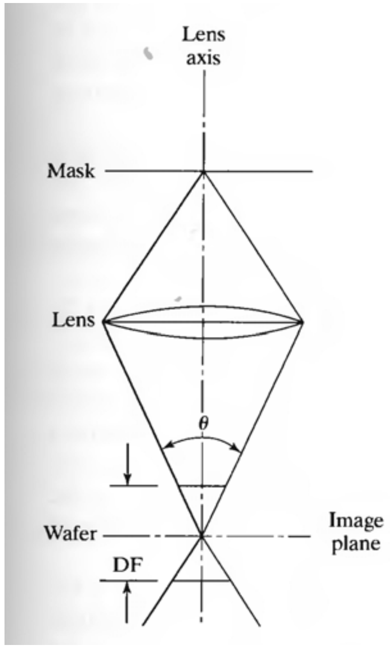
Resolution: The resolution indicates the smallest feature (F) or the spacing that can be produced in a manufacturing process. If we say that the resolution is 100 nm for a particular process, we mean that we can make any structure which is 100 nm size or larger or we can produce structures with a spacing of 100 nm or more. It also means that we probably cannot make structures which are smaller in size (like 50 nanometer) or smaller in gap repeatedly in this process.

The resolution depends on the wavelength of the light used and another parameter called "Numerical Aperture" (NA).

$$NA \propto \frac{Diameter}{Focal\ Length}$$

$$NA = n \times \sin(\theta / 2)$$

$$F \approx \lambda / NA$$



عمق کانونی

Depth of focus, also called depth of field, (DF) indicates how much variations one can accept in the planarity of the incoming wafer. For example if the incoming wafer is perfectly planer then it is easy to use the lithography process.

Usually the incoming wafer will have some variation in the topography (some ups and downs).

The lithography process should be able to print the patterns correctly even when there is poor planarity. This ability is quantified by the term “depth of field”.

Large depth of field and small resolution are preferred.

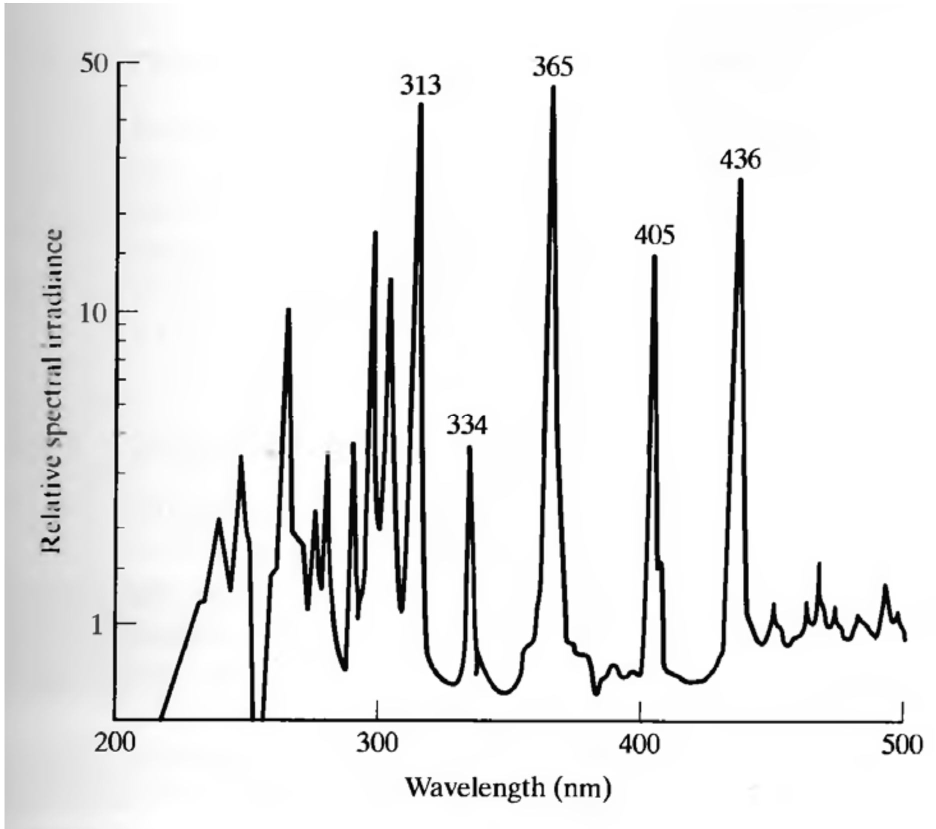
Unfortunately the depth of focus is related to the wavelength λ and the numerical aperture (NA).

$$DF = F / tg(\theta / 2) \approx F / \sin(\theta / 2) = n\lambda / (NA)^2$$

It is impossible to have large depth of field and still the smallest resolution. One has to make a compromise.

منابع نور

Originally visible light was used in lithography process. Later ultraviolet (UV) light was used.



Typical emission spectra from a Hg-Xe lamp.

436 nm (g-line)
365 nm (i-line)

منابع نور

With i-line lithography systems it is possible to reach 300 nm resolution.

Advanced lithographys systems use 248-nm KrF excimer laser (180 nm resolution), 193-nm ArF laser (100 nm resolution) and 157-nm F2 excimer laser (70 nm resolution) systems.

افزایش قدرت تفکیک

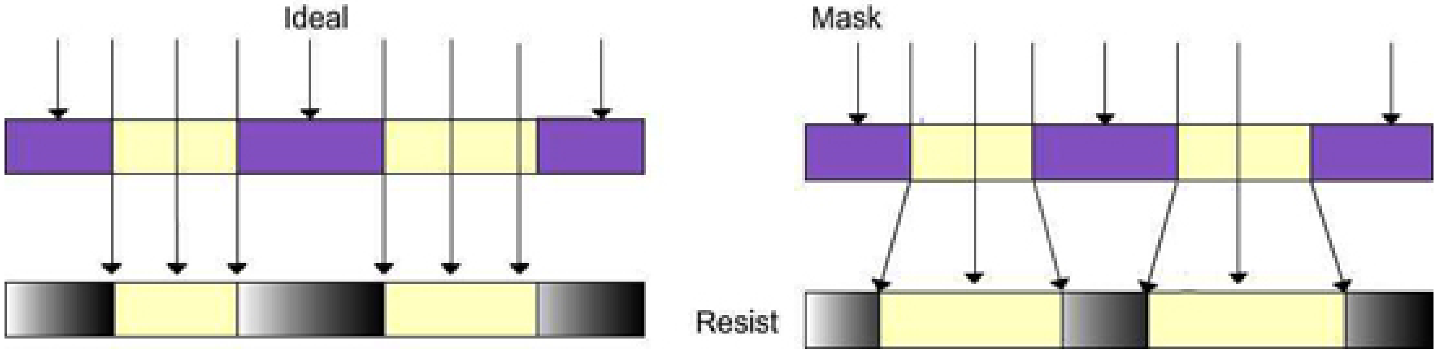
Now given a wavelength, how can we improve the resolution? There are certain techniques called resolution enhancement technique (RET).

We will consider 4 such techniques: one is optical proximity correction (OPC), second is antireflective coating (ARC), the third is phase shift mask (PSM), and the forth is Immersion Lithography.

OPC

OPC or Optical Proximity Correction: Proximity means ‘nearness’ or something in the vicinity. If we consider a metal line to be patterned in a particular location, the presence of a line nearby will affect the optical behaviour. If we want to print two lines next to each other in one case, and print one line with no other line near it in another case, then there is some difference in the behaviour of these two cases.

Optical proximity correction is a method to adjust the layout so that the differences are accommodated and the printing occurs as planned.



OPC

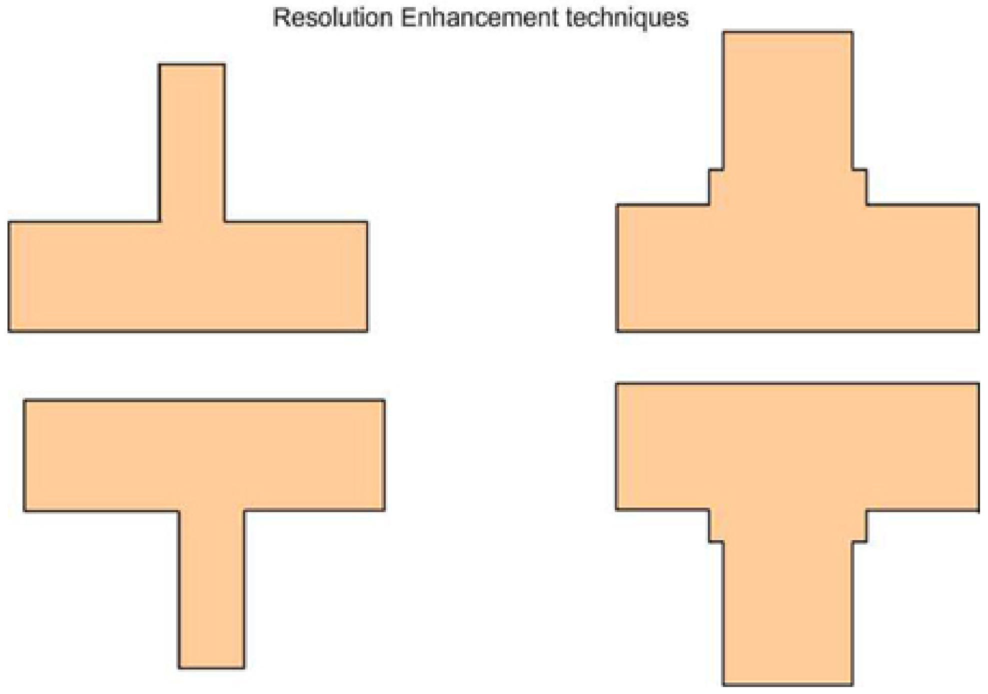
There is diffraction and hence the image on the wafer will be different compared to the image on the mask. Even if there is no other line nearby, the image will not be exactly the same as the one in the mask. In the case of line without any neighbour, called isolated line or iso line, the diffraction effects may make the image bit smaller than planned.

For example, if the mask contains 100 nm line, the image on the wafer may be only 90 nm. So, in order to print 100 nm line on the wafer, the mask can be made with 110 nm wide line. Please note that in this example, we are assuming that the mask is 1X mask and not the usual 4X mask. In case of a 4X mask, If we want 400 nm wide line, the mask may be made with 440 nm wide line. This method is called biasing.

In the lithography process, the presence of one line will affect the printing of another line, if the distance between the lines is within one micron. If the distance is more than one micron, the presence or absence of a line will not make any difference.

OPC

Adjacent T junctions in the layout (a) before OPC and (b) after OPC.



OPC can be classified as “rule based” or “model based”.

One point that we need to remember is that increase in the width is not the same as enlarging the layout. Here when the width is increased, the space gets reduced.

پوشش ضد بازتاب

Anti Reflective Coating: The second resolution enhancing techniques or RET is the application of anti reflective coating. This also called ARC or arc.

The incoming light and the reflected light within the film can form what is known as a standing wave. Essentially, the light reflected from the wafer will interfere with the light coming from the top. This will distort the image, and hence we will not get the exact image on the mask.

In order to overcome this problem, the following procedure is used. First, on the top of the wafer, a film made of a material called ARC or anti reflective coating is applied.

ماسک تغییر فاز

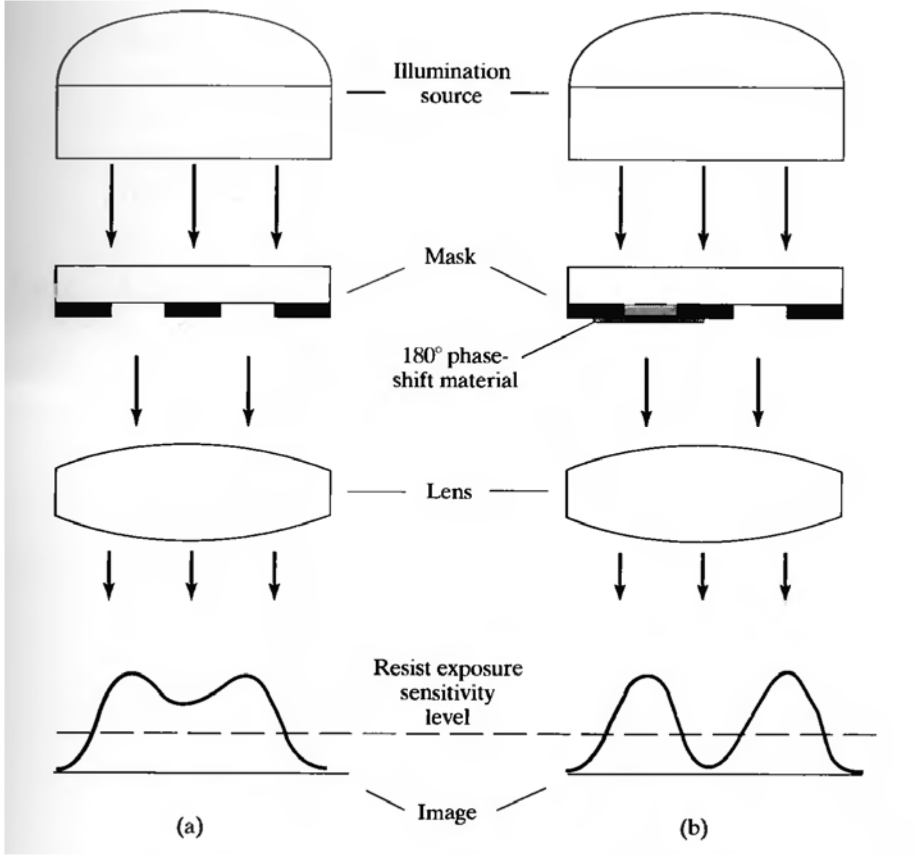
Phase Shift Mask:

The third RET is called phase shift mask or PSM. Earlier we saw that OPC can be used to account for diffraction to some extent. However, this trick can work only up to some extent. When the space between two features or two lines becomes very small, OPC will not work effectively. What is meant by very small? When these spaces and the widths are similar to the wavelength of the light used, then we can say that it is very small.

In the beginning of 2010, companies were creating chips with features of 65 nanometer size using light of 193 nanometer wavelength. This was possible only because they were using phase shift mask (PSM).

ماسک تغییر فاز

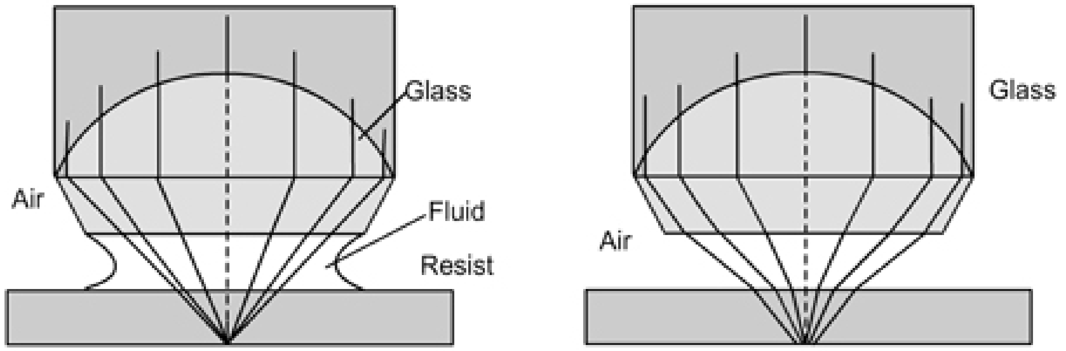
Pattern transfer of two closely spaced lines; (a) using conventional mask, (b) using phase shifted mask.



روش غوطه وری

Immersion Lithography: As of 2012, a technique called liquid immersion lithography is used. In this, a fluid such as water (or preferably with high refractive index) is introduced between the wafer and the lens. If the refractive index of the fluid matches that of the lens, (and assuming that the refractive index of the photoresist is similar to that of the lens) then the images formed at the bottom of the photo resist will be with high resolution.

The requirements of the fluid are that it must be compatible with the photo resist and the lens and that it should not absorb the light used (< 5% absorption). High purity water satisfies these requirements. Its refractive index is 1.47 and it can be doped with sulphates or phosphates to increase the refractive index slightly.



روش های لیتوگرافی پیشرفته

مزیت لیتوگرافی نوری این است که دارای سرعت زیاد (high throughput)، رزلوشن خوب، قیمت کم و کارکردن با آن اسان است. این روش برای ساخت در حیطه زیر میکرون دارای محدودیتهایی است.

اگرچه با روشهای افزایش تفکیک می توان تا حدودی مسئله را حل کرد ولی این روشها گران تمام می شوند. بنابراین بایستی بدنبال روشهای دیگری بود.

روشهای که برای این منظور بکار می روند عبارتند از:

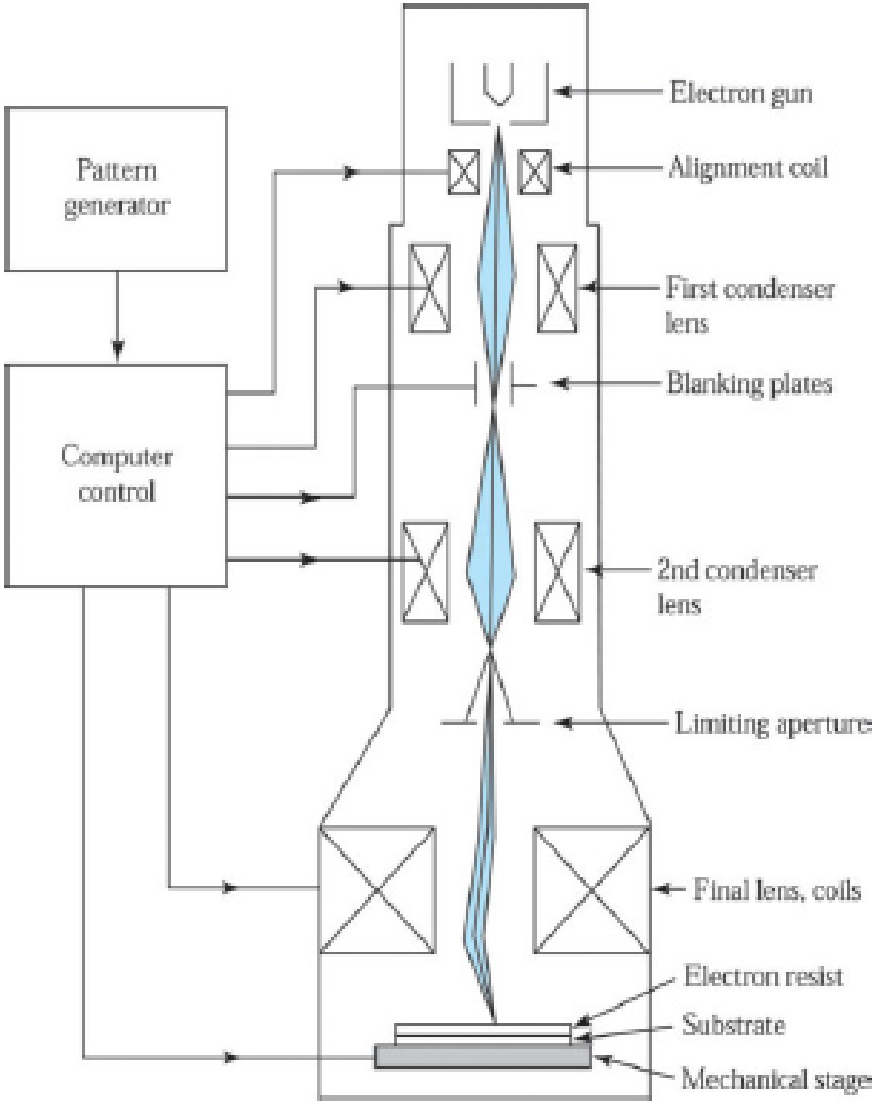
۱- لیتوگرافی پرتو الکترونی

۲- لیتوگرافی EUV

۳- لیتوگرافی اشعه X

۴- لیتوگرافی پرتو یونی

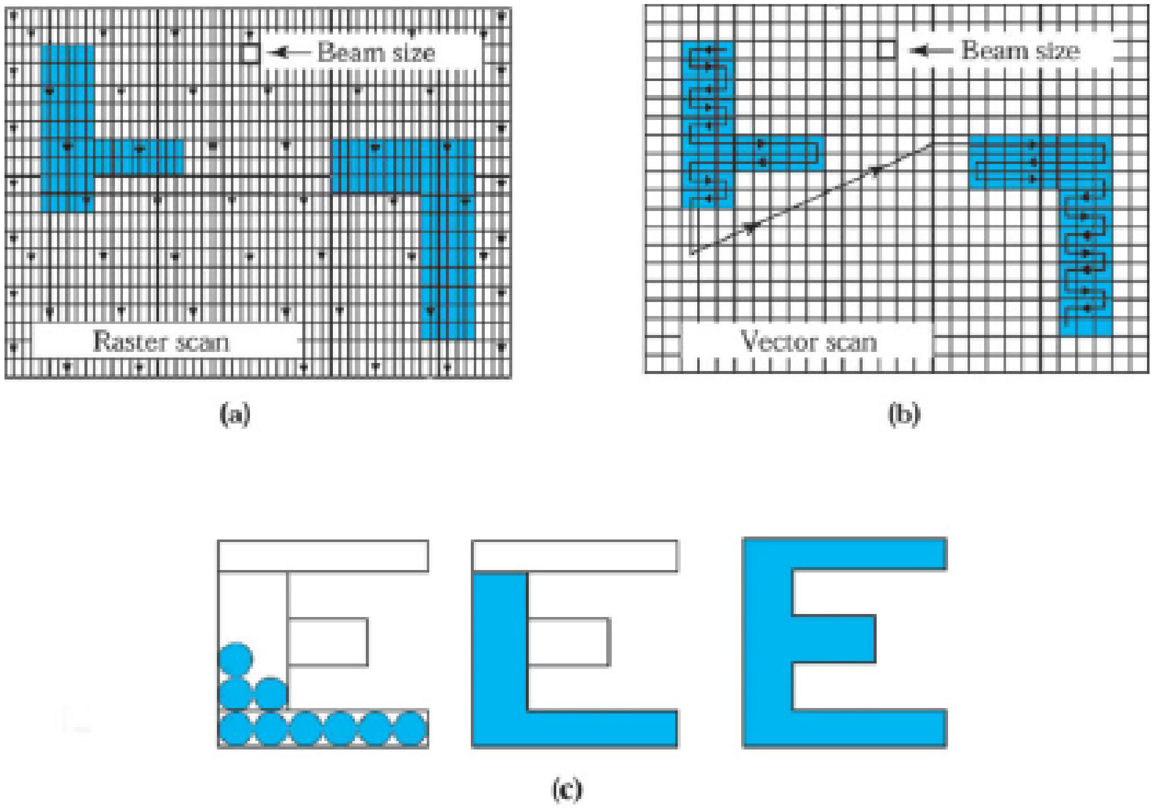
لیتوگرافی پرتو الکترونی



در روش لیتوگرافی پرتو الکترونی، پرتو الکترونی که توسط یک تفنگ الکترونی تولید می شود روی رزیست فوکوس می شود که قطر نقطه کانونی ۱۰ الی ۲۵ نانومتر می باشد. برای روشن وخاموش کردن پرتو صفحاتی جلو پرتو الکترونی را می بندند. در این روش نیازی به ماسک نیست.

نمایش طرحواره یک دستگاه لیتوگرافی پرتوالکترونی

لیتوگرافی پرتو الکترونی

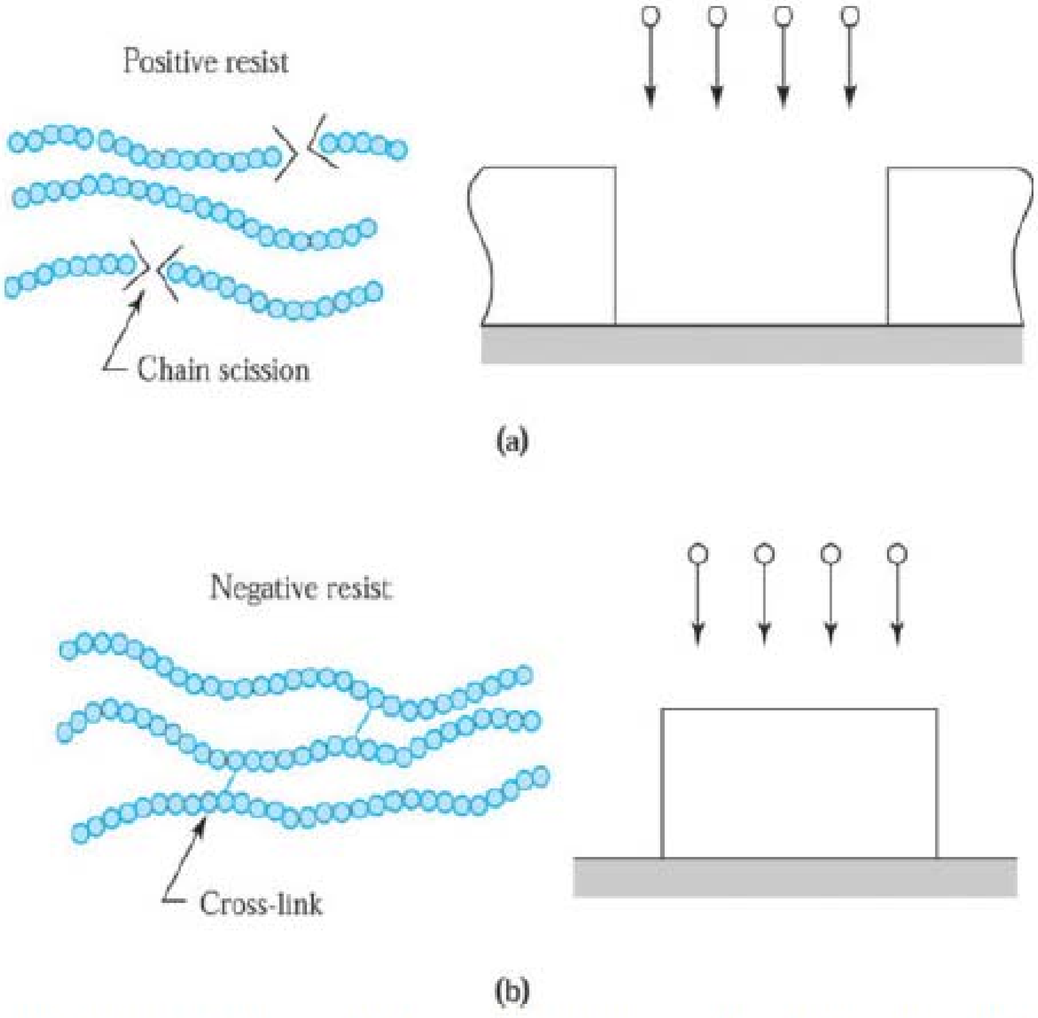


(a) (b)

(c)

(a) Raster-scan writing scheme; (b) vector –scan writing scheme; (c) shapes of electron beam: round, variable, and cell projection.

رزیست ها در لیتوگرافی پرتو الکترونی



Schematic of (*a*) positive and (*b*) negative resists used in electron-beam lithography.

برای لیتوگرافی پرتو الکترونی هم مثل لیتوگرافی نوری رزیست مثبت و رزیست منفی وجود دارد.

رزیست های مثبت معروف:

Poly-methyl methacrylate (PMMA)
Poly-butene-1 sulfone (PBS)

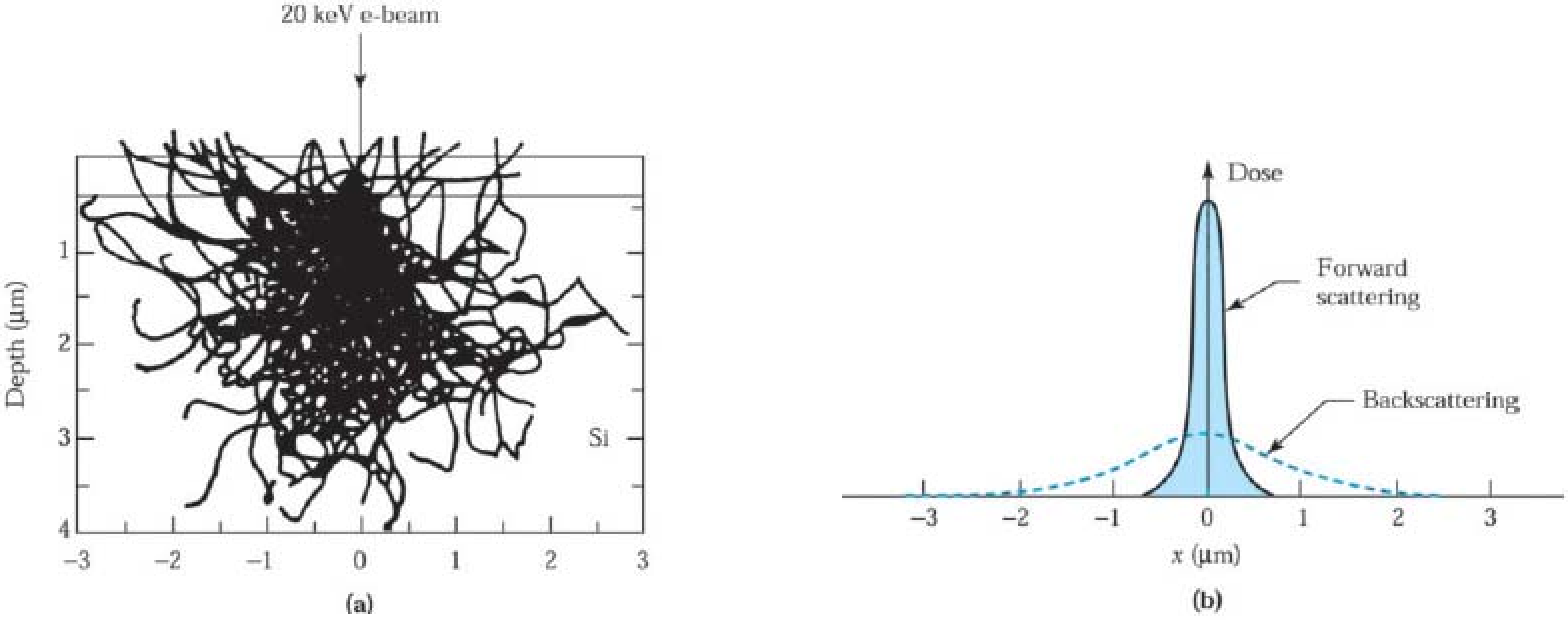
رزیست منفی معروف:

Poly-glycidyl methacrylate-co-ethyl-acrylate (COP)

با رزیست های مثبت می توان به رزلوشن ۱۰۰نانومتر و بهتر دست یافت. ولی با رزیست های منفی چون در حین دولوپ باد می کنند رزلوشن در حدودهای ۱ میکرومتر است

اثر نزدیک بودن (Proximity effect)

در لیتوگرافی پرتو الکترونی اثر پراش مهم نیست چراکه طول موج الکترون های چند کیلوالکترون ولتی و بالاتر کمتر از یک دهم نانومتر است. در این مورد پراکندگی الکترون ها اثر غالب را دارد. به علت پراکندگی تابش پرتو الکترونی به یک نقطه باعث خواهد شد تا نقاط نزدیک هم تحت تابش واقع شوند که به آن اثر نزدیک بودن گویند.



(a) Simulated trajectories of 100 electrons with initial energy of 20 keV incident at the origin of 0.4 micrometre film on thick Si substrate; (b) dose distribution of backward and forward scattered electrons at resist-substrate interface.

لیتوگرافی EUV

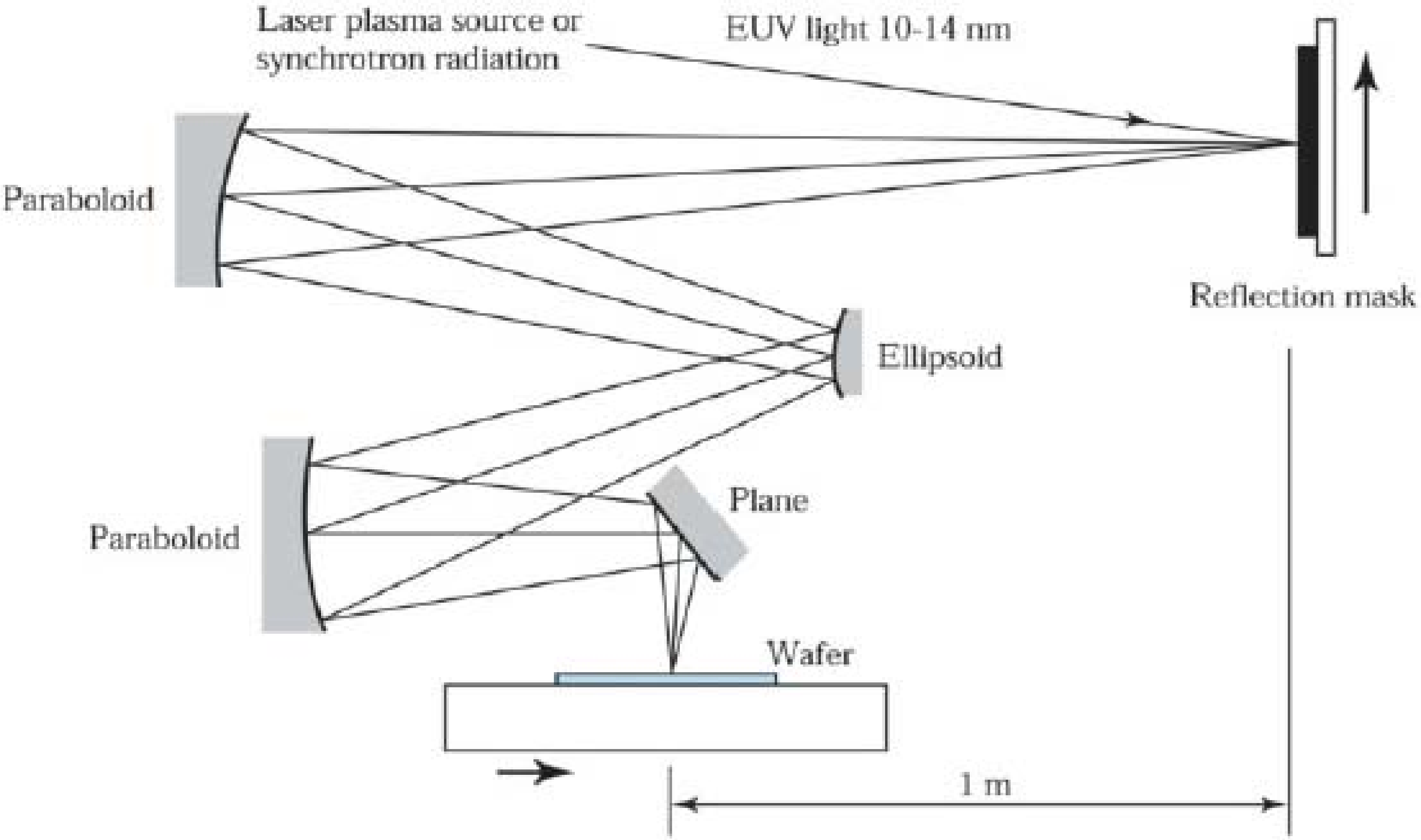
The Extreme Ultra Violet (EUV) lithography uses 10-14 nm radiation, and is capable of printing below 50 nm features without throughput losses. A laser produced plasma or synchrotron radiation can serve as EUV source.

Since almost all materials absorb EUV, the EUV lithography must be performed in vacuum. The mask and other optics would be using reflective method and not refractive method.

The mask and mirrors used must have multi layer coatings that produce quarter wave Bragg reflectors to maximize reflectivity.

EUV is capable of printing 50-20 nm features with PMMA resist using 13.5 nm radiation.

لیتوگرافی EUV



Schematic representation of an EUV lithography system.

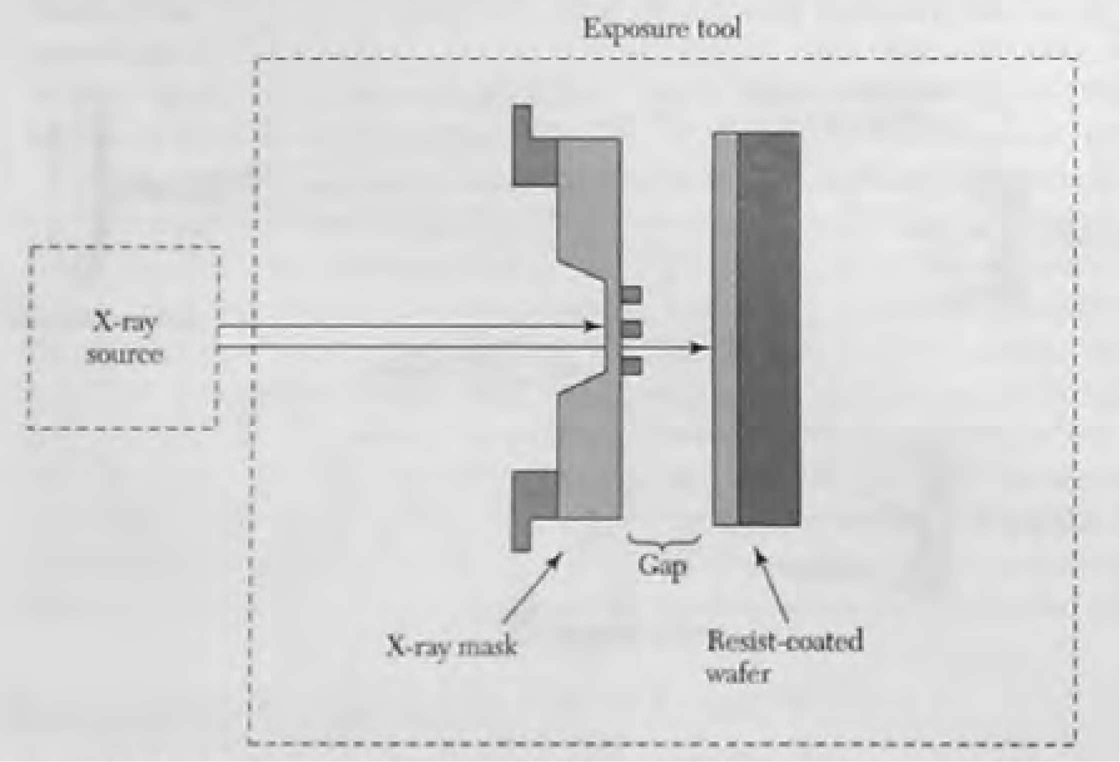
X لیتوگرافی اشعه

X-ray lithography is the extension of optical lithography to shorter wavelengths. Since X-rays have very short wavelengths (less than 1 nm), the diffraction limitations of normal lithography would not be present. Some of the difficulties faced are:
(a) it is difficult to bend and focus the X-rays and hence only 1X mask can be used and
(b) secondary electrons generated by X-ray causes contrast issues.

X-ray absorption depends on the atomic number of the material and most materials have low transparency at 1 nm, so the mask substrate must be a thin membrane (1-2 micrometres thick) made of low atomic number materials such as silicon or silicon carbide. The pattern itself is defined in a thin (0.5 micron), relatively high atomic number material such as, tantalum, tungsten, gold or one of their alloys, which supported by the thin membrane.

Since most dust particles will transmit X rays, particle contamination is less of an issue.

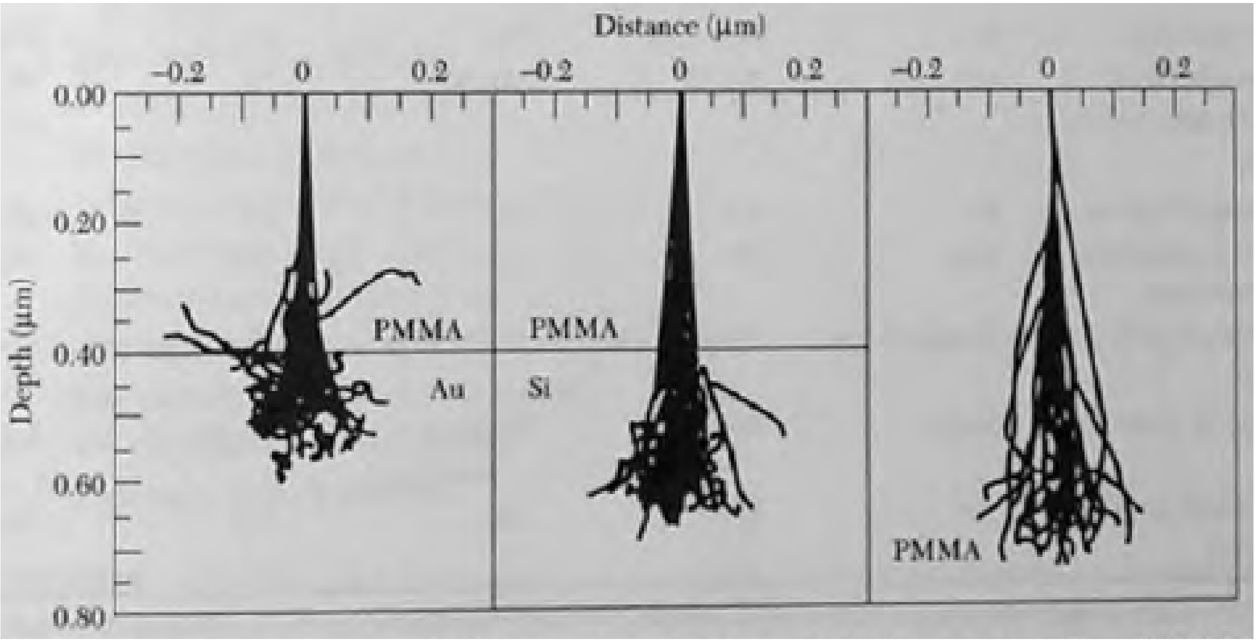
لیتوگرافی اشعه X



Schematic representation of x-ray lithography system.

لیتوگرافی پرتو یونی

Ion beam lithography can achieve higher resolution than optical, x-ray, or electron beam lithographic techniques because ions have higher mass and therefore scatter less than electrons. The most important application is the repair of masks for optical lithography.



Trajectories of 50 H+, with 60 keV energy travelling through PMMA into Au, Si, and PMMA.

شبیه سازی فرایندهای ساخت

نرم افزارهایی وجود دارند که کلیه فرایندهای ساخت یک افزاره نیم رسانا اعم از لیتوگرافی، سونش، نفوذ، اکسیداسیون و کاشت یون را می توان شبیه سازی کرد:

SUPREM

PROLITH

Silvaco Athena شامل بخش های مختلفی است که این کار را انجام می دهند. ویرایشهای جدید SUPREM ادغام شده در نرم افزار Athena است.

نرم افزارهای طراحی ماسک:

۱- L-EDIT ۲- LASI (http://lasihomesite.com)

۳- Silvaco Expert ۴- Layout Editor

۵- AutoCad